

A DEVICE AND METHOD TO DISCRIMINATE BETWEEN SUPRAVENTRICULAR TACHYCARDIAS AND VENTRICULAR ARRHYTHMIAS

Field Of Invention

This invention relates to the identification and detection of abnormal heart rhythm occurring in either the supraventricular or ventricular cardiac regions. Specifically, this invention relates to a novel method of analysis to discriminate between supraventricular tachycardia and ventricular arrhythmia. More specifically, this invention relates to an implantable cardiac defibrillator device controlled by a novel method of analysis to discriminate between supraventricular tachycardia and ventricular arrhythmia.

Background

Identifying the mechanism of an arrhythmia based on its intracardiac electrograms has become a common challenge to both implantable cardiac defibrillators (ICDs) and the physicians taking care of patients with ICDs. These devices, which are primarily designed to deliver therapy for life-threatening ventricular arrhythmia, frequently deliver inappropriate shocks for supraventricular tachycardias. These inappropriate shocks constitute a significant source of physical and emotional distress for patients, cause early ICD battery depletions, and generate a huge financial burden on the health system.

Inappropriate electroshocks from implanted cardiac defibrillators constitute a significant source of physical and emotional distress on the patients and an unnecessary expense for the health system. Early generations of implantable cardiac defibrillators operated with an incidence of inappropriate electroshocks as high as 20 to 40%. Tanaka S., *An Overview Of Fifth-Generation Implantable Cardioverter Defibrillator*, Ann Thorac Cardiovasc Surg., 4:303-311 (1998). Following the introduction of dual-chamber implantable cardiac defibrillators, however, the overall success for delivering appropriate electroshocks increased to 86 - 100%, while the successful incidence for the treatment of ventricular arrhythmias reached 97 - 100%.

The incidence of inappropriate electroshocks in response to supraventricular tachycardias, however, remains a problem. This problem is especially severe for

discriminating between supraventricular tachycardias having 1:1 antegrade conduction and ventricular arrhythmias having 1:1 retrograde conduction. Thompson *et al.*, *Ventriculoatrial Conduction Metrics For Classification Of Ventricular Tachycardia With 1:1 Retrograde Conduction In Dual-Chamber Sensing Implantable Cardioverter Defibrillators*, J
5 Electrocardiol., 31:152-156 (1988)

In an attempt to solve this problem, those skilled in the art have attempted using various mathematical algorithms to utilize the quantitative aspects of the ECG with variable success. Specifically, the morphology of a shocking electrogram may be compared to a sinus beat template. Gold *et al.*, *A New Defibrillator Discrimination Algorithm Utilizing*
10 *Electrogram Morphology Analysis*, Pacing Clin Electrophysiol. 1999;22:179-182 (1999)
Additionally, stability criteria may be employed to distinguish between atrial fibrillation and ventricular arrhythmia. Barold *et al.*, *Prospective Evaluation Of New And Old Criteria To Discriminate Between Supraventricular And Ventricular Tachycardia In Implantable Defibrillators*, Pacing Clin Electrophysiol., 21:1347-1355 (1998); and Schaumann *et al.*,
15 *Enhanced Detection Criteria In Implantable Cardioverter-Defibrillator To Avoid Inappropriate Therapy*, Am J Cardiol., 78:42-50 (1996). In comparison, discrimination between sinus tachycardia and ventricular arrhythmia may be determined by the employment of sudden onset criteria. These approaches have reduced the rate of inappropriate electroshocks, but continue to remain at approximately 11%. Schaumann *et al.* (*supra*).

20 The ability to reduce or avoid all inappropriate electroshocks from implantable cardiac defibrillators would have a beneficial effect on the physical and emotional state of patients with defibrillators as well as reduce the cost of health care. Clearly, what is needed in the art is a method and a device to prevent the misinterpretation of cardiac electrical signals and avoid the delivery of inappropriate electroshocks.

25 Summary

This invention relates to the identification and detection of abnormal heart rhythm occurring in either the supraventricular or ventricular cardiac regions. In one embodiment, the present invention contemplates a novel method of analysis to discriminate between

supraventricular tachycardia and ventricular arrhythmia. In another embodiment, the present invention contemplates a new implantable cardiac defibrillator device controlled by a novel method of analysis that discriminates between supraventricular tachycardia and ventricular arrhythmia.

5 The present invention contemplates a novel capability that detects an earliest arriving electrical signal (*i.e.*, an intracardiac electrogram) that discriminates between supraventricular tachycardia (SVT) and ventricular tachycardia (VT). This technique is based on intracardiac electrograms (EGMs) recorded by atrial and ventricular sensing leads that distinguish their temporal relationships following tachycardia recurrence subsequent to a train of simultaneous
10 anti-tachycardia pacing (ATP) bursts in the atria and ventricles.

One aspect of the present invention contemplates a device, comprising: a) a implantable pacemaker element; b) a implantable defibrillator element connected to said pacemaker element; and c) a plurality of atrial and ventricular pacing leads connected to said
pacemaker element, wherein said pacing leads are configured for simultaneous activation.

15 In one embodiment, the device further comprises a plurality of atrial and ventricular defibrillation leads connected to said defibrillator element. In another embodiment, the device further comprises a plurality of atrial and ventricular sensing leads connected to said pacemaker element. In yet another embodiment, the pacemaker element further comprises a storage memory connected to said sensing leads. In one embodiment, the device is capable of
20 detecting an earliest arriving electrical signal.

Another aspect of the present invention contemplates a method, comprising:
a) providing: i) a patient implanted with a device, comprising; 1) an implantable pacemaker element; 2) an implantable defibrillator element connected to said pacemaker element; and
3) a plurality of atrial and ventricular pacing leads connected to said pacemaker element,
25 wherein said pacing leads are configured for simultaneous activation and course to the ventricles and atria, wherein said pacemaker is capable of analyzing an electrocardiogram; ii) a plurality of sensing leads connected to said pacemaker coursing to the ventricles and atria; iii) a plurality of defibrillation leads connected to said defibrillator coursing to the ventricles;
b) detecting ventricular and atrial electrical signals by said sensing leads; c) identifying a
30 cardiac arrhythmia with said device; d) initiating one or more anti-tachycardia pacing bursts

by said pacemaker element, wherein said ventricles and atria are simultaneously paced; e) detecting an earliest arriving electrical signal following termination of said anti-tachycardia pacing burst. In one embodiment, a cardiac arrhythmia is detected in the patient. In one embodiment, the cardiac origin of a cardiac arrhythmia is determined by said earliest arriving electrical signal. In one embodiment, the earliest arriving electrical signal is from the ventricles. In another embodiment, the earliest arriving electrical signal is from the atria. In one embodiment, the method further comprises the step of defibrillating said ventricles under conditions such that normal sinus rhythm is restored.

Another aspect of the present invention contemplates a method, comprising:

a) providing; i) a patient; ii) an electrocardiogram array; iii) a plurality of intracardiac quadripole catheters, wherein said catheters are configured for simultaneous atrial and ventricular pacing; and iv) a computer configured to receive electrical signals from said catheters; b) placing said array on the skin surface of said patient; c) inserting said catheters into said patient; d) simultaneously pacing said atria and ventricle; e) detecting with said computer an earliest arriving electrical signal. In one embodiment, the earliest arriving electrical signal is from the ventricles. In another embodiment, the earliest arriving electrical signal is from the atria. In another embodiment, the earliest arriving electrical signal is from the junction between the ventricles and atria. In one embodiment, the method further comprises the step of diagnosing said patient as having ventricular tachycardia. In another embodiment, the method further comprises the step of diagnosing said patient as having supraventricular tachycardia. In yet another embodiment, the method further comprises the step of diagnosing said patient as having atrioventricular nodal reentrant tachycardia. In one embodiment, said computer is connected to a data readout device.

In a further aspect the present invention contemplates a method to detect the origin of a cardiac arrhythmia, comprising: a) providing; i) a patient exhibiting cardiac arrhythmia; ii) an array comprising sensing leads; iii) a computer connected to said array; and iv) pacing leads connected to said computer; b) simultaneously pacing the atria and ventricles with said pacing leads of said patient under conditions such that said patient atrial and ventricular activity is synchronized; and c) sensing with said sensing leads said atrial and ventricular

electrical activity after said pacing under conditions such that the earliest arriving electrical activity is detected.

Another aspect of the present invention contemplates a method, comprising:

5 a) providing: i) a patient implanted with a device, comprising; 1) an implantable pacemaker element; and 2) a plurality of atrial and ventricular pacing leads connected to said pacemaker element, wherein said pacing leads are configured for simultaneous activation and coursing to the ventricles and atria; and ii) a plurality of sensing leads connected to said pacemaker coursing to the ventricles and atria; b) initiating one or more pacing bursts by said pacemaker element, wherein said ventricles and atria are simultaneously paced; and c) detecting an
10 earliest arriving electrical signal following termination of said pacing bursts. In one embodiment, prior to step b), a cardiac arrhythmia is detected in said patient. In one embodiment, said earliest arriving electrical signal is from the ventricles. In another embodiment, said earliest arriving electrical signal is from the atria. In one embodiment, the method further comprises step d) defibrillating said ventricles under conditions such that
15 normal sinus rhythm is restored.

Another aspect of the present invention contemplates a method, comprising:

a) providing; i) a patient; ii) an electrocardiogram array; iii) a plurality of intracardiac quadripole catheters, wherein said catheters are configured for simultaneous atrial and ventricular pacing; and iv) a computer configured to receive electrical signals from said
20 catheters; b) placing said array on the skin surface of said patient; c) inserting said catheters into said patient; d) simultaneously pacing said atria and ventricles; and e) detecting with said computer an earliest arriving electrical signal. In one embodiment, the earliest arriving electrical signal is from the ventricles. In another embodiment, the earliest arriving electrical signal is from the atria. In yet another embodiment, the earliest arriving electrical signal is
25 from the junction between the atria and ventricles. In one embodiment, the method further comprising the step of diagnosing said patient as having ventricular tachycardia. In another embodiment, the method further comprises the step of diagnosing said patient as having supraventricular tachycardia. In yet another embodiment, the further comprises the step of diagnosing said patient as having atrioventricular nodal reentrant tachycardia. In one
30 embodiment, the computer is connected to a data readout device.

Yet another aspect of the present invention contemplates a method to detect the origin of a cardiac arrhythmia, comprising: a) providing; i) a patient exhibiting cardiac arrhythmia; ii) a system comprising a plurality of pacing leads and a plurality of sensing leads; b) simultaneously pacing the atria and ventricles of said patient; and c) sensing with said sensing leads said atrial and ventricular electrical activity after said pacing under conditions such that the earliest arriving electrical signal is detected. In one embodiment, the earliest arriving electrical signal is from the ventricles. In another embodiment, the earliest arriving electrical signal is from the atria. In yet another embodiment, the earliest arriving electrical signal is from the junction between the atria and ventricles. In one embodiment, the method further comprises the step of diagnosing said patient as having ventricular tachycardia. In another embodiment, the method further comprises the step of diagnosing said patient as having supraventricular tachycardia. In yet another embodiment, the method further comprises the step of diagnosing said patient as having atrioventricular nodal reentrant tachycardia. In one embodiment, the computer is connected to a data readout device.

In U.S. Pat. No.: 6,076,014 (herein incorporated by reference), an implantable dual chamber defibrillator capable of dual chamber pacing is disclosed. This defibrillator is revealed as capable of providing continuous atrial pacing or pacing of ventricular chambers as a response to a detected arrhythmia. The '014 patent does not disclose the simultaneous pacing of atria and ventricles to diagnose a tachycardia origin. Specifically, the '014 disclosure evaluates sensed ECG data by a fuzzy logic paradigm that is acknowledged to be imprecise. The fuzzy logic assessment in the '014 patent includes input regarding: i) atrial rates, ii) ventricular rates, iii) ECG morphology, iv) the historical trends of ECG data, and v) accelerometer data (*i.e.*, real-time measurement of patient movements)

The present application provides a novel method and device when compared to the '014 patent as well as being simple, specific, accurate. The disclosed capability of detecting an earliest arriving electrical signal reliably discriminates between ventricular arrhythmia and supraventricular tachycardia and objectively provides a defibrillation decision only for a condition of ventricular arrhythmia. Specifically, this capability relies on the relative arrival times of electrical activity from either the ventricles or the atria, after synchronization by simultaneous pacing. The '014 makes no mention of using anti-tachycardia pacing in

combination with a blanking period to assess which heart chamber resumes activity first. Instead, the '014 patent relies on IF-THEN statements that requires information on patient activity and the relative ventricular and atrial rates.

Definitions

5 As used herein, the term "cardiovascular disease" refers to any disease which affects the cardiovascular system including, but not limited to, nerve conduction disorders, thrombophilia, atherosclerosis, angina pectoris, hypertension, arteriosclerosis, myocardial infarction, congestive heart failure, cardiomyopathy, hypertension, arterial and venous stenosis.

10 "Symptoms of cardiovascular disease" as used herein refers to any clinical manifestation of a disease state associated with the heart and the central or peripheral arterial and venous vasculature. For example, said clinical manifestations include, but are not limited to pain, weakness, high blood pressure, elevated plasma cholesterol, elevated plasma fatty acids, tachycardia, bradycardia, abnormal electrocardiogram, external or internal bleeding, headache, dizziness, nausea and vomiting. Thus, a patient suffering from, or exhibiting
15 symptoms of, cardiovascular disease may detect certain symptoms (*i.e.*, pain), while other symptoms may not be noticeable to the patient, but are detectable by a health care provider (*i.e.*, elevated blood pressure).

20 As used herein, the term "patient" refers to a human or non-human organism that is either symptomatic or asymptomatic for cardiovascular disease. Preferably, a human patient is under the supervision of a physician or hospitalized.

25 As used herein the phrase, "patients at risk for cardiovascular disease" refer to patients who have an increased probability, as compared to the general population, of developing some form of cardiovascular disease in their lifetime. Patients at risk for cardiovascular disease generally have one or more risk factors for cardiovascular disease. Risk factors for cardiovascular disease include, but are not limited to, a history of smoking, a sedentary lifestyle, a family history of cardiovascular disease, lipid metabolic disorders, diabetes mellitus and obesity.

As used herein, the term "pathophysiological" refers to any condition in an individual or an organ that represents a significant deviation from established homeostatic norms. A pathophysiological alteration is not a structural defect.

As used herein, the term "electrocardiogram" (EKG or ECG) refers to any display of information reflecting changes in heart tissue membrane potentials in relationship to heart beat. The electrocardiogram comprises "electrogram activity" (EGM) that refers to any electrical signal detected by any sensing lead.

As used herein, the term "electrocardiogram array" refers to any arrangement of skin surface electrodes wherein the integration of the collected data results in the generation of an electrocardiogram.

As used herein, the term "skin surface" refers to the outer epithelial layer of a patient.

As used herein, the term "catheter" refers to any device that is used for the insertion and placement of electrocardiogram sensing leads into the intracardial space. Placement of such a device may be inserted into, but is not limited to, the femoral vein, then coursing through the vena cava and finally into the right atria and/or ventricle of the patient's heart.

As used herein, the term "coursing" refers to a path taken through a patient's body by an implanted catheter or electrical leads that may be, but are not limited to, those connected to an implanted ICD, pacemaker or combination thereof.

As used herein, the term "computer" refers to any device capable of receiving, storing and calculating data in an electronic format.

As used herein, the term "sinus rhythm" refers to a normal heart beat as quantified by the proper relationships between the P-Q-R-S-T electrocardiogram segments.

As used herein, the term "arrhythmia" refers to an abnormal heart beat as quantified by improper relationships between the P-Q-R-S-T electrocardiogram segments. Such arrhythmias may occur during, but are not limited to, ventricular arrhythmia, supraventricular tachycardia, ventricular fibrillation, atria fibrillation, and bradycardia.

As used herein, the term "atrial EGM" refers to electrogram activity from electrodes whose sensory input is limited to membrane potential changes of the atria. Specifically, these data are collected from, but is not limited to, a high right atrial intracardial electrode placed by catheterization.

As used herein, the term "ventricular EGM" refers to electrogram activity from electrodes whose sensory input is limited to membrane potential changes of the ventricles. Specifically, these data are collected from, but is not limited to, a right ventricular apex intracardiac electrode placed by catheterization.

5 As used herein, the term "depolarization" refers to the change in membrane potential that reflects the conduction of an "action potential" which initiates and coordinates the relative contractions of the left/right atria with the left/right ventricles. Specifically, these changes in membrane potential are generated by, but not limited to, the pacemaker cells residing in the right atrium.

10 As used herein, the term "direction of depolarization" refers to the movement of the electric potential across the heart surface. Specifically, an "antegrade" direction refers to a spreading of the depolarization from the atria onto the ventricles and subsequent proper coordination of the heart beat. On the other hand, a "retrograde" direction refers to a spreading of the depolarization away from the ventricles to the top of the atria and as a result
15 of ventricular arrhythmias.

As used herein, the term "data readout device" refers to any instrument that may be connected to a computer that receives and displays the results of computer calculations. These instruments may be, but are not limited to, an electronic monitor, a hardcopy printout, and an audible signal generated by a computer sound generation program.

20 As used herein, the term "cardiac defibrillator" refers to any device that generates an "electroshock" that is expected to restore normal sinus rhythm in a patient experiencing an abnormal ECG. These devices may include, but are not limited to, defibrillators that are safe and effective when surgically implanted in a patient and auto-activate upon sensing an abnormal ECG. Specifically, these devices may be, but are not limited to, dual-chamber
25 cardioverter-defibrillators. A "dual-chamber" design is preferred over other cardioverter-defibrillators because they provide an ability to simultaneously control the rate of ventricular and atrial contraction and sense their relative electrical activity.

As used herein, the term "inappropriate electroshock" refers to any electroshock generated by a cardiac defibrillator that is delivered by misinterpretation of an ECG. This

ECG misinterpretation may occur during, but is not limited to, sinus tachycardia or other supraventricular tachycardias.

As used herein, the term "pace" or "pacing" refers to an artificial electrical stimulation of a heart chamber that supersedes the function of physiological pacemaker cells. The artificial electrical stimulation may, but is not limited to, be generated by an electrode within an intracardiac catheter or an ICD.

As used herein, the term "atria" refers to the upper principal cavity of the heart auricle (*i.e.*, the sinus venosus) and is situated posteriorly to the smaller cavity of the auricle, the appendix auricula. The human heart comprises two atria, one on the left side of the heart and a second on the right side of the heart. Consequently, the term "atrial" references any matter of, or concerning, either one or both atria.

As used herein, the term "ventricle" refers to the lower, and largest, compartment of the heart. The human heart comprises two ventricles, one on the left side of the heart and a second on the right side of the heart. Consequently, the term "ventricular" references any matter of, or concerning, either one or both ventricles.

As used herein, the term "blanking period" refers to any cessation of electrogram (EGM) activity from either an atrial or ventricular chamber. A blanking period may be triggered by, but not limited to, an anti-tachycardia pacing (ATP) burst. Specifically, a blanking period is the shortest period of time, in milliseconds, as measured from the last ATP pacing burst that would include the first captured electrogram (EGM) activity from either the atrial and ventricular channels that varies as function of tachycardial cycle length. An exemplary calculation of a blanking period might be: $(100 + \text{TCL})/2$ where TCL is the tachycardia cycle length. The expected duration of a blanking period in a human patient is approximately, but not limited to, 100 - 500 msec.

As used herein, the term "anti-tachycardia pacing burst" refers to any train of electrical impulses generated from, for example, an implantable cardiac defibrillator or an external signal generator, during an episode of either supraventricular tachycardia or ventricular arrhythmia that provides pacing stimulus to either the atria, ventricles or both. Preferably, the generated signals are of a square-wave morphology. A "simultaneous anti-tachycardia pacing burst" refers to any pacing signals provided to both the atria and ventricle within any 0 - 40

msec timeframe. Generally, multiple anti-tachycardia pacing bursts are delivered, wherein each burst has an approximate length of twelve heart beats.

5 As used herein, the term "storage memory" refers to any electronic means that is capable of retaining digitized information or computer software programs. The digitized information may be binary or complex formulas or equations capable of receiving, and processing, input from atrial or ventricular sensing leads.

As used herein, the term "defibrillation leads" refer to any electrical conductive material placed on, or within, a heart chamber that, when activated, is capable of converting an abnormal heart rhythm into normal sinus rhythm.

10 As used herein, the term "sensing leads" refer to any electrical conductive material placed on, or within, a heart chamber that transmits electrical activity.

As used herein, the term "pacing leads" refer to any electrical conductive material placed on, or within, a heart chamber that, when activated, provides an electrical stimulus to control cardiac muscle contractility.

15 As used herein, the phrase "the capability of detecting an earliest arriving electrical signal" (or analogous phrases) refers to any electronic configuration that is capable of discriminating the arrival time between at least two electrical signals having a sensitivity of ranging between 0 - 40 msec. While not intending to limit any embodiment of the present invention, the sensing of atrial EGM or ventricular EGM may be performed with, or without, calculations based on any formula or equations. For example, EGMs may be filtered by the
20 pacemaker and connected to a timing device. The output may be, but is not limited to, a binary format. At a minimum, the detection capability answers two questions; i) Did the tachycardia terminate? (yes/no), and if it did not terminate, ii) Was the ventricular EGM prior to the atrial EGM? (yes/no).

25 As used herein, the term "earliest arriving electrogram activity" refers to the first electrical signal detected following a specific timeline marker (*i.e.*, an anti-tachycardia pacing burst).

As used herein, the term "simultaneously arriving electrogram activity" refers to at least two electrical signals detected within a 50 - 60 msec timeframe.

As used herein, the term "system" refers to any integrated single device, or multiple devices connected together, that function in a coordinated manner to produce a desired result. One example illustrated herein, describes a system that detects an earliest arriving electrical signal comprising integrated single device such as an implantable cardiac defibrillator comprising a pacemaker. Another example illustrated herein, describes a system that detects and earliest arriving electrical signal comprising multiple devices connected together such as an electrocardiogram array, a generator (*i.e.*, for example, pulse or signal) and a computer.

Brief Description Of The Drawings

Figure 1 depicts a cutaway drawing of an exemplary human heart showing the configuration of one embodiment of dual chamber implantable cardiac pacer/defibrillator.

Figure 2 shows a simplified flowchart of data flow and decision points in one embodiment of discriminating ventricular arrhythmia from supraventricular tachycardia and initiation of defibrillation.

Figure 3 shows successful termination of tachycardia in a human patient following 350 msec anti-tachycardia pacing bursts.

Figure 4A shows ventricular tachycardia persistence in a human patient following 400 msec anti-tachycardia pacing bursts. (blanking period from last ATP stimulation to dashed line)

Figure 4B shows ventricular tachycardia persistence in a human patient following 350 msec anti-tachycardia pacing bursts. (blanking period from last ATP stimulation to dashed line)

Figure 5 shows atrial tachycardia persistence in a human patient following 350 msec anti-tachycardia pacing bursts. (blanking period from last ATP stimulation to dashed line)

Figure 6 shows the presence of atrioventricular nodal reentrant tachycardia in a human patient following 360 msec anti-tachycardia pacing bursts. (blanking period from last ATP stimulation to dashed line)

Figure 7 shows an exemplary normal sinus rhythm tracing in a mouse.

Figure 8 shows ECG recordings using an octapolar catheter during atrial pacing using a Preva SR pacemaker in a mouse.

Figure 9 shows ECG recordings using an octapolar catheter during ventricular pacing using a Preva SR pacemaker in a mouse.

Figure 10 provides an ECG recording using an octapolar catheter illustrating that atrial activity is the earliest electrical activity following an anti-tachycardia pacing burst during a simulated supraventricular tachycardia by atrial pacing.

Detailed Description Of The Invention

This invention relates to the real-time identification and detection of abnormal heart rhythm occurring in either the supraventricular or ventricular cardiac regions. Specifically, this invention relates to a novel method of analysis to discriminate between supraventricular tachycardia and ventricular arrhythmia. More specifically, this invention relates to an implantable cardiac defibrillator device controlled by a novel method of analysis that discriminates between supraventricular tachycardia and ventricular arrhythmia.

The clinical manifestations of ventricular arrhythmias range from a complete absence of symptoms to sudden death. Although the understanding of the pathophysiology and natural history of these arrhythmias has advanced significantly over the past decade, large gaps in knowledge remain, especially in patients with heart failure not due to coronary artery disease. Many symptomatic ventricular arrhythmias, however, are now curable using catheters that deliver radio-frequency energy (*i.e.*, ablation lesioning). It is now clear that the primary treatment for patients at high risk for life-threatening ventricular arrhythmias is the implantable cardiac defibrillator.

Determination of atrial tissue depolarization directionality has met with little success. Various time and frequency domain criteria have been mathematically applied to the bipolar atrial electrogram, which achieve successful discrimination of atrial depolarization directionality in less than 80% of patients. Timmis *et al.*, *Discrimination Of Antegrade From Retrograde Atrial Electrograms For Physiologic Pacing*, PACE 11:130-140 (1988); Wainwright *et al.*, *Ideal Atrial Lead Positioning To Detect Retrograde Atrial Depolarization By Digitization And Slope Analysis Of The Atrial Electrogram*, PACE 7:1152-1158 (1984). Similarly, the use of amplitude and slew rate criteria resulted in successful discrimination of

antegrade versus retrograde atrial depolarization in 81% of patients (McAlister *et al.*, *Atrial Electrogram Analysis: Antegrade Versus Retrograde*, PACE 11:1703-1707 (1988)). This in contrast to an initial promising study that could not be reproduced. Pannizo *et al.*, *Discrimination Of Antegrade And Retrograde Atrial Depolarization By Electrogram Analysis*, Am Heart J. 112:780-786 (1986).

The advent of atrioventricular conduction metrics improved the discrimination between ventricular arrhythmia and 1:1 supraventricular tachycardia where 80% specificity was coupled with 100% sensitivity when ventriculoatrial times were between 80 and 234 ms. Thompson *et al.*, *Ventriculoatrial Conduction Metrics For Classification Of Ventricular Tachycardia With 1:1 Retrograde Conduction In Dual-Chamber Sensing Implantable Cardioverter Defibrillators*, J Electrocardiol., 31:152-156 (1988) Beyond these boundaries, both the sensitivity and specificity were 100%. Similarly, correlational waveform analysis was able to discriminate between antegrade and retrograde atrial activation, in the absence of ventricular arrhythmia, during ventricular pacing when patient-specific thresholds were adopted and the sampling rate of the signal was set at 1,000 Hz or greater. Throne *et al.*, *Discrimination Of Retrograde From Antegrade Atrial Activation Using Intracardiac Electrogram Waveform Analysis*, Pacing Clin Electrophysiol., 12:1622-1630 (1989)

The impact of heart rate and sympathetic tone on the shape of intracardiac ECG waveforms has been assessed. In 36 out of 39 patients, increased heart rates resulting from; i) atrial pacing, ii) epinephrine infusion, and iii) isoproterenol infusion did not significantly alter ECG waveform configuration as assessed by correlation waveform analysis. Finelli *et al.*, *Effects Of Increased Heart Rate And Sympathetic Tone On Intraventricular Electrogram Morphology*, Am J Cardiol. 68:1321-1328 (1991) In patients with permanent pacemakers, exercise results in a 38% decrease in atrial ECG amplitude without any other morphologic changes. Ross *et al.*, *The Effect Of Exercise On The Atrial Electrogram Voltage In Young Patients*, PACE, 14:2092-2097 (1991) The correlation coefficients (ρ) generated by correlation waveform analysis is independent of amplitudes and units and should not be adversely impacted by heart rate, sympathetic tone or exercise. Woodroffe M., *Probability With Applications*, McGraw-Hill, New York. pp. 229 (1975) It is possible, however, that

changes in atrial morphology may occur over time and changing patient posture. A critical analysis of these variables would require the use of chronic sensing leads.

Heart Function

5 The operation of the heart is regulated by electrical signals produced by the heart's sino-atrial (SA) node. Each signal produced by the SA node spreads across the atria and ventricles of the heart, depolarizing the muscle fibers as it spreads. Atrial and ventricular contractions occur as the signal passes. After contracting, the myocardial cells repolarize during a short period of time, returning to their resting state. Once repolarized, the muscle cells are ready to be depolarized again by a signal from the SA node.

10 At rest, the normal adult SA node produces a signal approximately 60 to 85 times a minute, causing the heart muscle to contract, and thereby pumping blood to the remainder of the body. This constitutes the repetitive, cyclic behavior of the heart. Each cycle in the operation of the heart is called a cardiac cycle.

15 Atrial geometry, atrial anisotropy, and histopathologic changes in the left or right atria can, alone or together, form anatomical obstacles. The obstacles can disrupt the normally uniform propagation of electrical impulses in the atria. These anatomical obstacles (called "conduction blocks") can cause the electrical impulse to degenerate into several circular wavelets that circulate about the obstacles. These wavelets, called "reentry circuits," disrupt the normally uniform activation of the left and right atria. Abnormal, irregular heart rhythm called arrhythmia, results. This form of arrhythmia is called atrial fibrillation, which is a very prevalent form of arrhythmia.

20 To analyze the heart's operation, a variety of techniques have been developed for collecting and interpreting data concerning the electrical activity of the heart. One of the most basic of these approaches is the electrocardiogram (ECG). As an electrical signal spreads across the heart, an ECG repetitively measures the voltages at various electrodes relative to a designated "ground" electrode. The ECG typically plots each lead over an interval of time such that the heart's electrical activity for one or more cardiac cycles is displayed for purposes of monitoring or analysis. The three most common ECG's are known as the "12 lead", the "18 lead," and the vector cardiograph.

A cardiac cycle as measured by the ECG is partitioned into three main elements which reflect the electrical and mechanical operation of the heart. The portion of a cardiac cycle representing atrial depolarization is referred to as a "P-wave." Depolarization of the ventricular muscle fibers is represented by "Q", "R", and "S" points of a cardiac cycle.

5 Collectively these "QRS" points are called an "R-wave" or a "QRS complex." The portion of a cardiac cycle representing repolarization of the ventricular muscle fibers is known as a "T-wave." It is through the use of an ECG that one is able to determine whether fibrillation is or is not occurring and allows one to manipulate the heart tissue to provide treatment.

Pacemakers

10 A pacemaker maintains the heart rate of a patient between a certain programmable range. For example, in humans that range is typically between 60-80 beats per minute (lower rate) and 120-160 beats per minute (upper rate). In one embodiment, the present invention contemplates a pacemaker for stimulating the independent conduction zones and reestablishing functional communication between the zones. A pacemaker automatically applies a pacing
15 impulse to the heart of sufficient magnitude to depolarize the tissue. The device is adapted to continue delivering intermittent pacing to the heart in the event that the heart fails to return to its normal behavioral pattern, and has the ability of automatically regaining sensing control over a functional heart, thereby insuring that further pacing is inhibited.

The pacemaker circuit comprises two basic subsystems; a sensing system, which
20 continuously monitors heart activity; and a stimulation system which upon receiving a signal from the sensing system applies a pacing impulse to the myocardium through an intravascular electrical lead. A first bipolar lead may be coupled to the pulse generator and has an electrode located at its distal end to sense and pace the atrium. Alternatively, the atrial leads may comprise separate sensing and pacing electrodes. A second bipolar lead coupled to the
25 generator is used for sensing and pacing the ventricle. Alternatively, the ventricular leads may comprise separate sensing and pacing electrodes. A circuit is provided for applying impedance measuring current pulses between one of these electrodes and the others.

In one embodiment, an off-the-shelf pacemaker is capable of both atrial and ventricular pacing/sensing. The specific pacemakers preferred for this purpose include a Medtronic

Sigma, a Medtronic Kappa (both made by Medtronic, Inc. Minneapolis, MN), a Guidant Discovery, a Guidant Meridian (both made by Guidant Inc, Minneapolis, MN) or Pacesetter Affinity (Pacesetter, a St. Jude's company, Minneapolis, MN) as these have a minimum programmable delay between atrial and ventricular pacing of 10 msec. To effectuate pacing according to one embodiment of the invention, all leads from the atrial and the ventricular segment of the pacemaker are connected to the atrium and ventricle, respectively. To allow more than one segment to be paced per lead, a bifurcation system can be used. Such leads are commercially available and can be used as an off-the-shelf product. The Y-adapter (for example CPI MODEL #6835, or #6024, made by Cardiac Pacemakers Inc., Minneapolis, MN) would allow one of the sockets from the pacemaker (atrial or ventricular) to then be bifurcated to at least two leads. Therefore, each output would then be able to pace at least two electrically isolated segments. For epicardial pacing, CPI model #4312 lead (Cardiac Pacemakers Inc., Minneapolis, MN) can be used and this has a 4.75 mm pin. For endocardial pacing, CPI model #4161 (Cardiac Pacemakers Inc., Minneapolis, MN) could be used. In this manner, a standard dual chamber pacemaker could be used to pace four intracardial segments.

Sensing Elements Of A Pacemaker

In a standard dual chambered pacemaker, the sensing circuits monitor activity both in the atrium and ventricle. If a sensed event occurs in the atrium, this initiates a ventricular paced event if no ventricular activity occurs during the programmed atrio-ventricular delay. If no sensing occurs in the atrium or ventricle, pacing is initiated to maintain the programmed lower rate.

When the pacemaker device is used for the present invention, similar sensing algorithms will be useful in the appropriate pacing of the various intracardiac segments. It is particularly desirable that the pacemaker include a sensor of a physiologic parameter related to demand for cardiac output, such as an activity sensor, a respiration sensor or an oxygen

saturation sensor. Various dual chamber pacing devices have incorporated some form of sensor to provide a physiologic pacing rate. Similar sensing is contemplated for the present invention to maintain a physiologic rate.

Pacing Elements

5 In a standard dual chamber pacemaker, pacing of both atrium and ventricle is possible. In the current invention, pacing of the various elements will take place once requested by the sensing algorithm. The standard burst generator pacemaker employs appropriate technology for the generation of stimulation pulses in the form of individual pulses or pulse trains having an amplitude up to 7 V and a pulse width of up to 1 msec. Most pacemakers have these
10 parameters as a programmable option. The pacing rate is also programmable in most pacemakers and the range is between 35 - 160 beats/min.

Given that the circuitry for pulse generation has become well known to those skilled in the art, no detailed disclosure is included herein. Specific timing, amplitude, duration and the number of pulses is controlled by a microprocessor via data bus under the control of a
15 program stored in memory.

Implantable Cardiac Defibrillators

Implantable cardiac defibrillators have significantly reduced the risk of sudden death following hospital discharge, but arrhythmia risk and associated mortality remains an important problem. Buxton *et al.*, *Current Approaches To Evaluation And Management Of*
20 *Patients With Ventricular Arrhythmias*, Med Health R I, 84(2):58-62 (2001) Arrhythmias are known to occur in patients having congestive heart failure, atrial fibrillation, ventricular tachyarrhythmias, and bradyarrhythmias. Atrial fibrillation, in particular, is treatable with rate control anticoagulation or cardioversion followed by maintenance of sinus rhythm. In patients surviving malignant ventricular arrhythmias, however, implanted cardiac defibrillators are
25 especially beneficial. Specifically, in patients with coronary artery disease, decreased ejection fraction, with or without nonsustained ventricular tachycardia, defibrillator implantation can improve survival. Lampert *et al.*, *Management Of Arrhythmias*, Clin Geriatr Med, 16(3):593-618 (2000)

Identifying the mechanism of an arrhythmia based on intracardiac electrograms has become a challenge in the clinical use of implantable cardiac defibrillators. Implantable cardiac defibrillators are primarily designed to deliver therapy for life-threatening ventricular arrhythmias but frequently deliver inappropriate shocks during supraventricular tachycardias.

5 Tanaka S., *An Overview Of Fifth-Generation Implantable Cardioverter Defibrillator*, Ann Thorac Cardiovasc Surg., 4:303-311 (1998); Thompson *et al.*, *supra*; Gold *et al.*, *A New Defibrillator Discrimination Algorithm Utilizing Electrogram Morphology Analysis*, Pacing Clin Electrophysiol. 1999;22:179-182 (1999); Barold *et al.*, *Prospective Evaluation Of New And Old Criteria To Discriminate Between Supraventricular And Ventricular Tachycardia In*
10 *Implantable Defibrillators*, Pacing Clin Electrophysiol., 21:1347-1355 (1998); and Schaumann *et al.*, *Enhanced Detection Criteria In Implantable Cardioverter-Defibrillator To Avoid Inappropriate Therapy*, Am J Cardiol., 78:42-50 (1996)

A Dual Chamber Pacing/Sensing Device

Figure 1 provides one possible embodiment contemplated by the present invention; for
15 example, an implantable cardiac defibrillator 13 attached to pacemaker 14. One of skill in the art will easily recognize that the scope of the present invention is not limited by the device herein described. In fact, many possible engineering designs are compatible with the embodiments described herein. It is not intended, therefore, to limit the present invention to the device depicted in Figure 1.

20 The pacemaker/defibrillator is implanted in a surgically-formed pocket in the flesh of the patient's chest 10, or other desired location of the body. Signal generator 14 is conventional and incorporates electronic components for performing signal analysis and processing, waveform generation, data storage, control and other functions, power supply (battery or battery pack), which are housed in a metal case (can) 15 compatible with the tissue
25 and fluids of the body (*i.e.*, biocompatible). The device is microprocessor-based with substantial memory, logic and other components to provide the processing, evaluation and other functions necessary to determine, select and deliver appropriate therapy including electrical defibrillation and pulses of different energy levels and timing for ventricular

defibrillation, cardioversion, and pacing to the patient's heart 16 in response to ventricular arrhythmia and supraventricular tachycardia.

Composite electrical lead 18 which includes separate leads 22 and 27 with distally located electrodes is coupled at the proximal end to signal generator 14 through an electrical connector 20 in the header of case 15. Preferably, case 15 is also employed as an electrode such as electrical ground, for unipolar sensing, pacing or defibrillation. Unlike the defibrillator devices used in previous methods, the signal generator and lead(s) of the present invention may be implemented for atrial and ventricular sensing, pacing and defibrillation. Defibrillating shocks of appropriate energy level may be applied between the case and electrode 21 on lead 22 implanted in the right atrium 24 through the superior vena cava 31, or between the case and electrode 26 on lead 27 implanted through the superior vena cava in the right ventricle 29. Leads 22 and 27 and their associated distal tip electrode 32 (to a separate conductor) and distal tip electrode 35 (also to a separate conductor within the lead), respectively, may be used for both a sensing lead and a pacing lead in conjunction with the circuitry of signal generator 14. One of skill in the art may easily recognize that separate sensing and pacing leads are also compatible with this described system. To that end, electrode 32 is positioned in the right atrium against either the lateral or anterior atrial wall thereof, and electrode 35 is positioned in the right ventricle at the apex thereof.

Active or passive fixation of the electrodes may be used to assure suitable excitation. Tip electrode tip 35 preferably has a standard 4 to 8 millimeter (mm) configuration, and is provided with soft barbs (tines) to stabilize its position in the ventricle. Each of the electrodes, those used for defibrillation and cardioversion, as well as those used for sensing and for pacing, are electrically connected to separate conductors in leads 22 and 27.

If desired, rather than simply using metal case 15 as an electrode, a conductive pouch 37 comprised of a braided multiplicity of carbon fine, individual, predominantly isotropic wires such as described in U.S. Pat. No. 5,143,089 (herein incorporated by reference) is configured to receive, partly enclose and maintain firm electrical contact with the case. This serves to enhance the effectiveness of the anodal electrode of the case and establish a better vector for the electric field produced by the defibrillation shock waveform, and thereby lower the defibrillation threshold. The conductive pouch can be electrically connected directly to an

extension lead 38 composed of similar carbon braid of about 7 french diameter which is implanted subcutaneously for connection to an epicardial or pericardial patch electrode (not shown) or as a wire electrode (as shown) through an opening formed by puncture surgery at 39. The conductor for electrode 36 of lead 38 may be implanted subcutaneously to a point 5 39, and then by puncture surgery through the thoracic cage and the pericardial sac, under a local anesthetic. The lead 38 is run parallel to the sternum, through the puncture, and then through the patient's thoracic cage and into the pericardial sac. It may even be threaded through the thoracic cage, the pericardial space about the left ventricle and atrium, and back along the right atrial appendage, external to the heart. The distal end 36 of lead 38 is 10 preferably placed close to the left atrium of the patient's heart to provide an increase in electric field strength and support the strong vector of the electric field according to the heart chamber to be defibrillated. Selection of the chamber (*i.e.*, atrium or ventricle) which is to undergo defibrillation is made by choosing the appropriate endocardial counter-electrode (21 or 26, respectively) to be energized together with the carbon electrode, if the case 15 or conductive pouch 37 is not used directly as the other electrode.

Fabricating the electrode portion of conductor 38 (from the point of entry 39 into the thoracic cage) of carbon braid provides the desirable features described earlier herein. Proper intracardiac positioning improves the vector for defibrillation through the atrium as well as the ventricle.

20 Atrial coil electrode 21 is used for bipolar sensing as well as a counter-electrode for defibrillation. Hence, electrode 21 is preferably also composed of a braided carbon fiber material described in the '089 patent, to take advantage of its very low polarization and low defibrillation threshold, to allow the intrinsic rhythm to be detected almost immediately after delivery of a shock for accurate determination of the current status of electrical activity of the 25 atrium. The features of low polarization and accurate sensing are important for detection and evaluation of atrial status since atrial signals have magnitudes of only about 20% to 25% those of ventricular signals because of the smaller atrial mass. The braided carbon fiber structure of electrode 21 is also desirable to provide a large effective electrical surface area (for example, in a range from three to six square centimeters) relative to its considerably 30 smaller geometric area, which provides greater energy efficiency for defibrillation.

As with atrial electrode 21, ventricular electrode 26 of lead 27 is positioned for use as a defibrillation electrode as well as for bipolar sensing in the ventricle. For defibrillation, electrode 26 also cooperates with the metal case 15, pouch electrode 37, or pericardial electrode 36, whichever of these latter electrodes is used in the defibrillator implementation.

5 Again, a braided conductive structure for electrode 26 provides it with an effective surface area considerably larger than its actual exposed surface area. As an alternative, the electrode may be composed of fine metallic filaments and fibers of platinum iridium alloy, braided together to offer similarly desirable electrode characteristics.

Thus, the tip electrodes of leads 22 and 27 are used for sensing and pacing of the
10 respective atrial and ventricular chambers as in a conventional pacemaker, with dual-chamber pacing, dual-chamber sensing, and both triggered and inhibited response. Further, the defibrillator 13 uses a transvenous electrode for ventricular defibrillation and stimulation and an atrial bipolar lead for sensing and atrial defibrillation, so that atrial defibrillation is performed with one of the same electrodes used for atrial stimulation and
15 sensing.

Rather than terminating at distal tip electrode 32, the latter electrode may be positioned at mid-lead of the atrial transvenous lead 22 which extends and is threaded through right atrium, ventricle, pulmonary valve, and into the left pulmonary artery, with a coil counter-electrode 42 connected to a separate conductor of the lead. With this alternative
20 embodiment, a defibrillating waveform can be applied between electrode 42 and atrial defibrillation electrode 21 upon detection of atrial fibrillation. In that configuration, electrode 42 would replace signal generator case 15, conductive pouch 37, or lead portion 36 as the selected electrode, and enables a strong vector for the electric field through right and left atrium. Rather than placement in the left pulmonary artery, electrode 42 may be positioned in
25 the distal coronary sinus for defibrillation of the atrium in conjunction with electrode 21.

Defibrillation of the atrium and ventricle is achieved by application of defibrillation waveforms of suitable shape and energy content between appropriate electrodes, such as electrode 36 and electrode 21 for atrial fibrillation, or between electrode 42 and electrode 21 for atrial fibrillation; or between electrode 36 and electrode 26 for ventricular fibrillation, in
30 which atrial electrode 21 can be used additionally as either anode or cathode. The case 15

can serve as the anode for delivery of the shock as well, and can provide ground reference potential for unipolar sensing and pacing, in both chambers.

Data Collection

One embodiment of the present invention contemplates an implantable cardiac
5 defibrillator (ICD) that differentiates between supraventricular tachycardia and ventricular arrhythmia based on whether the atria or ventricles initiate an electrical signal first following a cessation of anti-tachycardia pacing.

Figure 2 demonstrates how one embodiment of the present invention discriminates
between one of three situations below that might be present during abnormal tachycardia:

- 10 1. The ventricular electrical activity is sensed prior to the atrial electrical activity:
The arrhythmia is originating from the ventricles and, therefore, defibrillation is required.
2. The ventricular electrical activity is sensed after the atrial electrical activity:
The arrhythmia is originating from the atria and, therefore, defibrillation is not
15 required.
3. The ventricular electrical activity is sensed almost simultaneously with the atrial
electrical activity: This scenario is compatible with a special form of
supraventricular tachycardia known as atrioventricular nodal reentrant
tachycardia which originates from the junction between the atria and the
20 ventricles and depolarizes these cardiac chambers almost simultaneously. This
form of supraventricular tachycardia is not life-threatening and therefore
defibrillation is inhibited in this situation.

One embodiment of the present invention contemplates an ICD that responds to
tachycardia by delivering simultaneous anti-tachycardia pacing bursts (*i.e.*, for example, for a
25 period of, but not limited to, 10 heart beats) to both the atria and ventricles at a cycle length approximately equal to, but not limited to, 80% of the cycle length of the tachycardia.

Preferably, the cycle length is modified by altering the ICD programming. In one
embodiment, tachycardia is terminated subsequent to the delivery of the anti-tachycardia
pacing burst and obviates the need for an immediate origin diagnosis and defibrillation.

30 Preferably, following tachycardia termination the ICD continues to receive EGM activity from

both the ventricular and atrial sensing leads. In another embodiment, the ICD maintains storage capability such that all electrical activity sensed from the ventricles and atria are accessible for downloading for later diagnosis of tachycardial events not requiring defibrillation. In another embodiment, tachycardia is not terminated subsequent to the delivery of the anti-tachycardia pacing burst and the ICD then determines whether the atrial channel or the ventricular channel recorded the first electrical activity after a blanking period (*i.e.*, for example, for a length of, but not limited to, 200 msec) following the anti-tachycardia pacing burst. Preferably, the blanking period is modified by altering the ICD programming. In a preferred embodiment, the ICD does not defibrillate if the first sensed electrical activity is atrial (*i.e.*, diagnosed as a supraventricular tachycardia). In another preferred embodiment, the ICD does defibrillate if the first sensed electrical activity is ventricular (*i.e.*, diagnosed as a ventricular arrhythmia). In one embodiment, the ICD does not defibrillate upon an almost simultaneous sensing of electrical activity from both the atria and ventricle, wherein said simultaneous electrical activity occurs within, but not limited to, a 60 msec timeframe (*i.e.*, diagnosed as an atrioventricular nodal reentrant tachycardia).

In another embodiment, simultaneous anti-tachycardia pacing bursts to the atria and ventricles controlled by catheter-inserted quadripole electrodes results in a termination of the existing tachycardia arrhythmia. Figure 3 depicts the last three pacing square wave beats of 350 msec duration from an anti-tachycardia pacing burst (STIM), where the atrial activation (HRA d and HRA p) is clearly simultaneous with both ventricle activation (RVA p) and His bundle activation (HIS - p, n & d). Following the cessation of the ATP, a normal P-Q-R-S-T profile is visible (arrow) on the HRA p lead, thus indicating a return to normal sinus rhythm.

In another embodiment, simultaneous anti-tachycardia pacing bursts to the atria and ventricles identifies the ventricles as originating the tachycardial event. Figure 4A shows the last three pacing beats induced by a burst of 400 msec square wave depolarizations (STIM) triggering a blanking period (blanking period from last ATP stimulation to dashed vertical line). After the blanking period, ventricular activity is recorded (see RVA d; arrow) prior to atrial activity (see MAP d; arrow). Similarly, Figure 4B also shows first arriving ventricular activity except that the pacing beats were induced by 350 msec stimulus (STIM) and atrial activation is recorded on HRA d (see arrow) and HRA p leads and compared with ventricular

data recorded on RVA p and RVA d leads (see arrows). Ventricular tachycardia is diagnosed as persistent in both tracings because the ventricular electrical signal appears prior to the atrial electrical signal during the blanking period.

In another embodiment, simultaneous anti-tachycardia pacing bursts to the atria and ventricles identifies the atria as originating the tachycardial event. Figure 5 shows the last two pacing beats induced by a 350 msec stimulus (STIM) triggering a blanking period (blanking period from last ATP stimulation to dashed vertical line). After the blanking period, atrial activity is recorded (see HRA d or HRA p; arrows) prior to ventricular activity (RVA p or RVA d; arrow). Supraventricular tachycardia is diagnosed as persistent because the atria electrical signal appears prior to the ventricular electrical signal during the blanking period.

In another embodiment, simultaneous anti-tachycardia pacing bursts to the atria and ventricles identifies the junction between the atria and ventricles as originating the tachycardia event. Figure 6 shows the last four pacing beats induced by a 360 msec stimulus (STIM) triggering a blanking period (blanking period from last ATP stimulation to dashed vertical line). After the blanking period, atrial activity (HRA d), ventricle activity (RVA p) and His bundle activity (HIS d) all appear simultaneously. Atrioventricular nodal reentrant tachycardia is, therefore, diagnosed.

Experimental

The following are examples that further illustrate embodiments contemplated by the present invention. It is not intended that these examples provide any limitations on the present invention.

EXAMPLE I

Anti-Tachycardia Pacing Responses In Patients Exhibiting Supraventricular Tachycardia And Ventricular Tachycardia

This example provides data collected during an electrophysiological testing study demonstrating the effectiveness of anti-tachycardia pacing bursts in patients exhibiting supraventricular or ventricular tachycardia.

A total of twelve patients (three female and nine male) were tested having a mean age of 61 ± 19 years. A summary breakdown of the patients by characteristics and response to anti-tachycardia pacing for patients is shown in Table 1 below:

Table 1: Summary Patient Data For Electrophysiological Testing Study

	SVT	VT
Number of Patients	8	4
Age (years)	59 ± 21	65 ± 16
% Female	37	0
Left Ventricular Ejection Fraction (%)	52 ± 11	$32 \pm 10^*$
% Having Cardiac Disease		
None	75	0
CAD	25	100
Reason For Electrophysiological Study		
SVT	4	0
VT	0	4
Other (syncope, palpitation etc)	4	0
Number of ATP bursts per patient	6.0 ± 4.1	8.7 ± 4.7
% Termination per patient	44 ± 33	17 ± 22

(*) $p < 0.02$

The combined average left ventricular ejection fraction was $45 \pm 14\%$ but there was a significant difference between the eight patients diagnosed as having supraventricular tachycardia (SVT: $52 \pm 11\%$) versus the four patients diagnosed as having ventricular tachycardia (VT: $32 \pm 10\%$). Of the four ventricular tachycardia patients all had a previous

history of cardiac disease. However, only two of the eight supraventricular tachycardia patients reported any previous history of cardiac disease. The remaining four of the supraventricular tachycardia patients presented with symptoms such as syncope or palpitations.

Patients were tested in the fasting state and under conscious sedation (0.5-2 mg Midazolam). Lidocaine (1%) was used for local anesthesia while venous sheaths (6 Fr or 7 Fr) were inserted into the femoral veins. Quadripolar (5 mm inter-electrode distance and 1.5 mm electrode thickness) were inserted into the venous sheaths and coursed into the high right atrial, His bundle and right ventricular apical positions that were verified by fluoroscopy observation.

Comparisons of continuous variables between groups was performed using the Student t-test. Discrete variables were compared using Fisher's exact test. A p value < 0.05 was considered to be statistically significant.

Catheters were connected to a recording system and a stimulator (EPMed System, NY) via a junction box. If an arrhythmia was induced during the course of the electrophysiologic study and the patient remained hemodynamically stable, then attempts at terminating the arrhythmia using anti-tachycardia pacing (ATP) bursts was performed. The ATP bursts were delivered from the external stimulator by simultaneous pacing of the atrium and ventricle at a rate corresponding to approximately 80% of the arrhythmia cycle length. The response of the arrhythmia to ATP was then recorded. ATP bursting continued until the arrhythmia terminated or the patient became hemodynamically unstable, at which time the arrhythmia was terminated by external cardioversion (*i.e.*, full-body electroshock).

The arrhythmia were classified as ventricular (VT) or supraventricular (SVT) by the attending electrophysiologist based on guidelines well known in the art. Analysis of the response of the arrhythmia to ATP bursting was noted, as well as the earliest electrical recording (*i.e.*, whether recorded on atrial sensing leads or ventricular sensing leads).

Responses were classified in one of the following categories:

1. Termination of Arrhythmia: This response is exemplified in Figure 3. No further electrogram (EGM) activity analysis was performed.

2. Ventricular Tachycardia Persistence: This response is exemplified in Figures 4A and 4B. During the blanking period, the earliest EGM activity was recorded by the ventricular sensing leads.
3. Supraventricular Tachycardia Persistence: This response is exemplified in Figure 5. During the blanking period, the earliest EGM activity was recorded by the atrial sensing leads.
4. Atrioventricular Nodal Reentrant Tachycardia Persistence: This response is exemplified in Figure 6. During the blanking period, the earliest EGM activity was simultaneously recorded (*i.e.*, within 50-60 msec) on both the atrial and ventricular sensing leads. However, for the purposes of the present example only, this condition was diagnosed as a supraventricular tachycardia arrhythmia.

Anti-tachycardia pacing bursts were initiated a total of eight-three times between the twelve patients. The SVT group experienced forty-eight pacing bursts (6.0 ± 4.1 per patient) while VT group experienced thirty-five pacing bursts (8.7 ± 4.7 per patient). Following twenty-two of the anti-tachycardia pacing bursts, the tachycardia was terminated, while the tachycardia persisted following the remaining sixty-one bursts. The computer algorithm correctly discriminated the first arriving cardiac electrical signal in all sixty-one of the persisting tachycardias and properly diagnosed twenty-nine persisting tachycardias as supraventricular and thirty-two persisting tachycardias as ventricular.

As such, this protocol results in a 100% sensitivity and a 100% specificity and demonstrates one example of a capability of detecting a first arriving electrical signal that discriminates extremely well between ventricular and supraventricular tachycardias.

EXAMPLE II

Anti-Tachycardia Pacing In An Experimental Mouse Model

This example demonstrates that the mouse may be utilized as an experimental model to study earliest arriving electrical activities following anti-tachycardia pacing to identify the source of cardiac tachycardia.

Female FVB mice were anesthetized with xylazine and ketamine (IP) coadministered with propranolol to reduce the intrinsic heart rate. Under a Nikon surgical microscope, a 1.7 French octapolar catheter (NuMed Inc., Hopkinton, NY) was introduced through the right jugular vein coursing into the right atrium and right ventricle of the mouse. The electrode spacing on the catheter tip is 0.5 mm and the electrode thickness is 0.5 mm. A six lead surface electrogram was obtained from the mouse by placing one subcutaneous electrode into each limb of the mouse, for a total of four. The surface electrograms were filtered at 0.01 Hz to 100 Hz, and intracardiac signals sampled at 1 KHz, amplified and filtered at 30 to 500 Hz (LabSystem Duo Bard Electrophysiology, Lowell, MA).

Demand pacing was achieved by using a single chamber Preva SR pacemaker (Medtronic Inc., Minneapolis, MN) set to pace at a very fast rate (up to 400 beats per minute) in temporary mode. The bipolar output of the pacemaker was connected by alligator clips to the proximal pins of the intracardiac catheter for atrial pacing and the distal pins for ventricular pacing. The catheter was also connected to an external stimulator (Bloom Associates Ltd., Reading, PA) configured to pace simultaneously the atria and ventricles of the mouse through the proximal and distal pins, respectively.

The proper placement of the catheter was verified by the collection and analysis of a normal sinus rhythm. Figure 7 illustrates a mouse ECG having a normal P-Q-R-S pattern on the surface channel (Lead I) at a cardiac cycle length of approximately 180-200 msec (320-300 beats per minute). Note that on the intracardiac channels (see, for example, IC5), the A and V electrograms correspond to the P and QRS complexes on the surface electrogram, respectively. Specifically, note that atrial EGM activity (A) occurs prior to ventricular EGM activity (V), as expected in sinus rhythm.

Figure 8 illustrates atrial pacing stimuli (S) at a cycle length of 180-200 msec (approximately 320-300) beats per minute to simulate a supraventricular tachycardia. The vertical black lines indicate the pacing stimulus (S) followed by the atrial EGM (A) and the ventricular EGM (V), annotated in Lead IC3. Similar to the normal sinus rhythm data shown in Figure 7, Lead IC3 of Figure 8 shows the normal electrocardiogram sequence, with atrial EGM activity (A) occurring prior to ventricular EGM activity (V). Also, the surface P-Q-R-S complex (Lead I) is similar to that of the normal sinus rhythm tracing seen in Figure 7.

Figure 9 shows ventricular pacing stimuli (S) at a cycle length of 160-180 msec (approximately 375-320 beats per minute), to simulate ventricular tachycardia. The vertical black lines indicate the pacing stimulus (S) followed by the P-Q-R-S response pattern, annotated in Lead IC7. Contrary to the above data in Figures 7 and 8, Lead IC7 of Figure 9 shows a reversal of the usual P-Q-R-S complex. Specifically, ventricular EGM activity (V) occurs first, followed by atrial EGM activity (A). Also, note that the surface P-Q-R-S pattern (Lead I) during ventricular pacing is different than during sinus rhythm and atrial pacing (see Figures 7 & 8, respectively).

Figure 10 shows an exemplary tracing of the earliest arriving electrical activity after ATP on the atrial channel following at least one simultaneous atrial and ventricular anti-tachycardia pacing (ATP) burst of up to 12 beats per burst with a cycle length of 150-160 msec (approximately 400-375 beats per minute). During simultaneous atrioventricular ATP bursting, the pacemaker output simulating the supraventricular tachycardia was inhibited. After the last beat of simultaneous atrioventricular ATP (Lead IC3; Sa+v: arrow), and an approximate 75-100 msec blanking period, the earliest electrical activity recorded was atrial EGM activity (A). Note that pacemaker stimulus (S) resumed following the cessation of ATP bursting and prior to the first arriving atrial EGM activity.

In summary, sixty-nine ATP bursts were delivered in two mice, forty-five during atrial pacing and twenty-four during ventricular pacing. The earliest electrical activity after ATP was detected on the atrial channel in all forty-five atrial pacing attempts. Similarly, the earliest electrical activity after ATP was detected on the ventricular channel in all twenty-four ventricle pacing attempts.

As such, this protocol results in a 100% sensitivity and a 100% specificity and demonstrates one capability of detecting a first arriving electrical signal that discriminates extremely well between ventricular and supraventricular tachycardias.